The Block Research Group (BRG) at the Institute of Technology in Architecture, ETH Zurich, led by Philippe Block and Tom Van Mele, focuses on research in equilibrium analysis, computational form-finding and the fabrication of curved-surface structures. Here, **Philippe Block** describes how

Philippe Block

PARAMET
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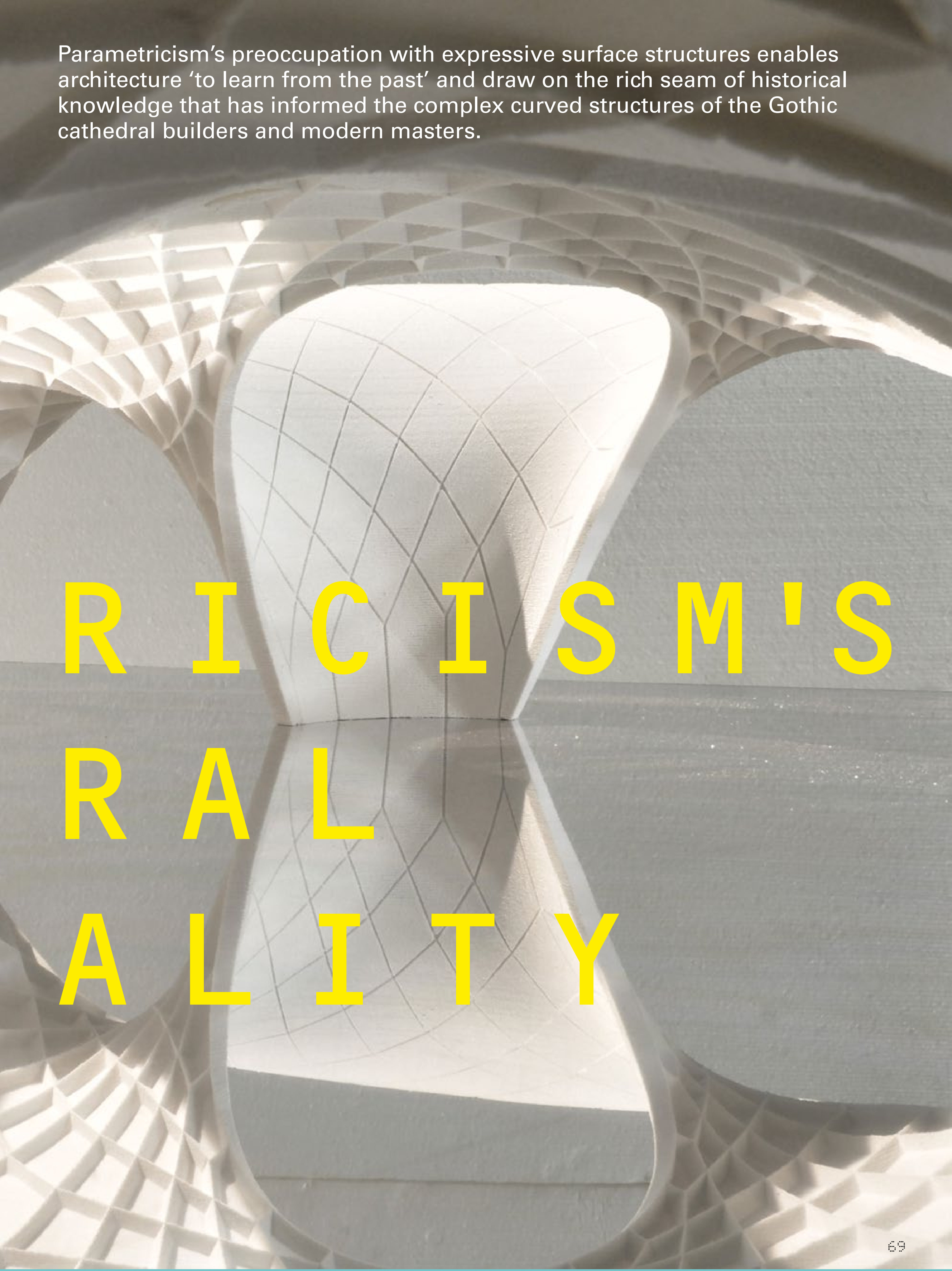
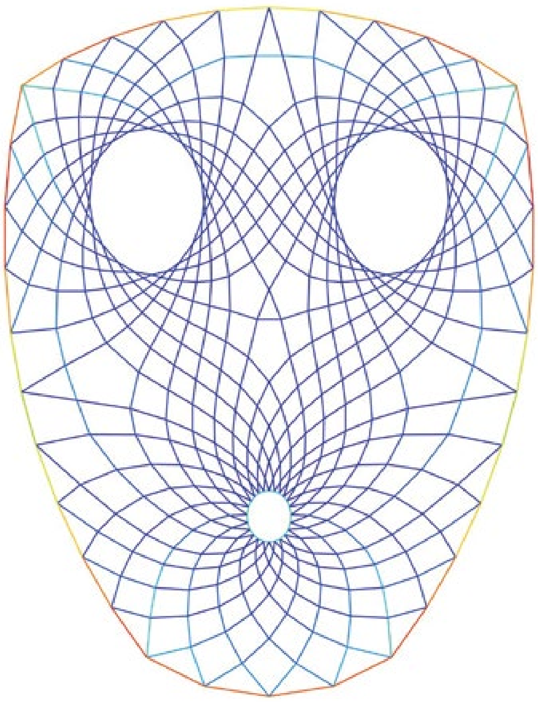
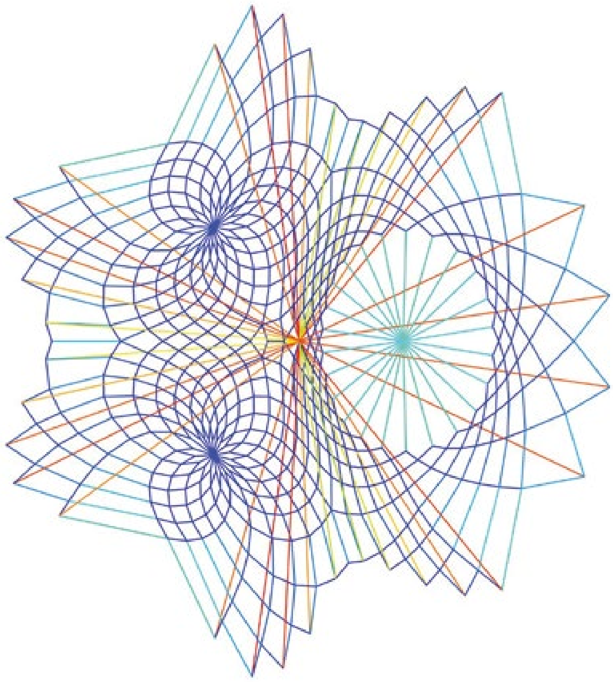
Parametricism's preoccupation with expressive surface structures enables architecture 'to learn from the past' and draw on the rich seam of historical knowledge that has informed the complex curved structures of the Gothic cathedral builders and modern masters.

R I C I S M ' S R A L A L I T Y







Block Research Group (BRG), Funicular funnel shell, ETH Zurich, 2013

previous spread and above: Controlling the flow of forces through explicit form and force diagrams, the new graphical form-finding approaches developed by the BRG allow the careful shaping of expressive and structurally efficient shells. This shell acts in compression on the inside, balanced by a tension ring along the cantilevering perimeter.

The design and construction of shell structures is an inherently historical field, the greatest examples having been realised in the past. These reach back to the Gothic era, with its sensational stone cathedrals, to the tile vaulting of Rafael Guastavino at the turn of the 20th century, and more recently to the period of the great shell builders of the 1950s and 1960s led by the likes of Eduardo Torroja, Félix Candela and Heinz Isler in reinforced concrete, or Eladio Dieste in reinforced brick. It is only now, however, that this knowledge is being reintroduced and enhanced through new research.

Thanks to recent innovations in structural engineering, particularly in the development of extremely flexible and fast structurally informed computational design methods, as well as in multi-criteria optimisation techniques, the gap between structural and architectural complex curved geometry is narrowing. The potential of this newly generated knowledge is that it allows for truly holistic designs that find a balance between form and force. The terms 'expressive' and 'structurally efficient' are no longer oxymoronic, but can be synonymous. Parametricism proposes a style that capitalises on expressive surface structures, allowing geometry in architecture to adequately address the complex, dynamic and programmatic requirements of contemporary institutions.

LEARNING FROM THE PAST: THE DECLINE AND CHALLENGES OF SHELLS

The use of continuous shell structures in architecture and the knowledge required for their design and construction declined significantly from the 1960s for a number of reasons. Firstly, they are difficult to integrate into programmatic needs, particularly in multilevel buildings, and they present a variety of issues in the arena of building physics, as well as challenges in architectural detailing. Formally they fell out of fashion, especially during the rise of 20th-century Modernism. Given the typical costs involved in the construction of formwork, they are materially and labour intensive, and ultimately the available types of optimised geometry for shell structures have until recently been limited.

Despite these many challenges, however, the use of shell structures can also offer opportunities, as will be argued here. By proposing a style that is dominated by expressive surface structures, Parametricism can utilise complex geometry to address the multifarious demands of contemporary architecture, for example by providing more intuitive and natural ways to navigate space using the inherent semiological potentials of shapes. It thus addresses one of the above-mentioned key reasons why shell structures have fallen into disuse: the challenge of integrating programmatic needs in an elegant manner.

In no small way, this reason for the declining use of shell structures may be attributed to issues of building physics; for example, how to avoid thermal bridges,

how to integrate insulation without covering a shell's surface, or how to interface with vertical walls or in between floors. The inherent flatness of floors is at odds with the continuous curves of a shell structure. An astonishing structure like Félix Candela's posthumous Oceanogràfic in Valencia, an oceanarium representing various marine habitats that was completed in 2003, arguably loses its eloquence – visible only during its construction phase – right after the formwork has been taken out; once that raw construction is filled with walls, facades, building systems, lighting and so on, it becomes a less compelling form. How might shells be designed so they are also floors, or how can floors become shells? Finding a language – and an efficient and cost-effective means of construction – that integrates shells beyond their occasional appearance as singular building roofs or pavilion structures offers great potential to return meaning and purposefulness to these elegant structural systems.

Félix Candela, Oceanogràfic, Valencia, Spain, 2003

top: After Candela's death in 1997, engineers Carlos Lázaro and Alberto Domingo of CMD Ingenieros continued this oceanarium project, realising the shell as a thin sheet of only 6 centimetres (2 inches) in steel-fibre concrete spanning 40 metres (130 feet).

designtoproduction, Destroyed formwork of SANAA's Rolex Learning Center, Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland, 2009

above: The custom CNC-cut shuttering of the optimised/simplified formwork of the university study centre's concrete shell reduced to a pile of non-reusable waste.

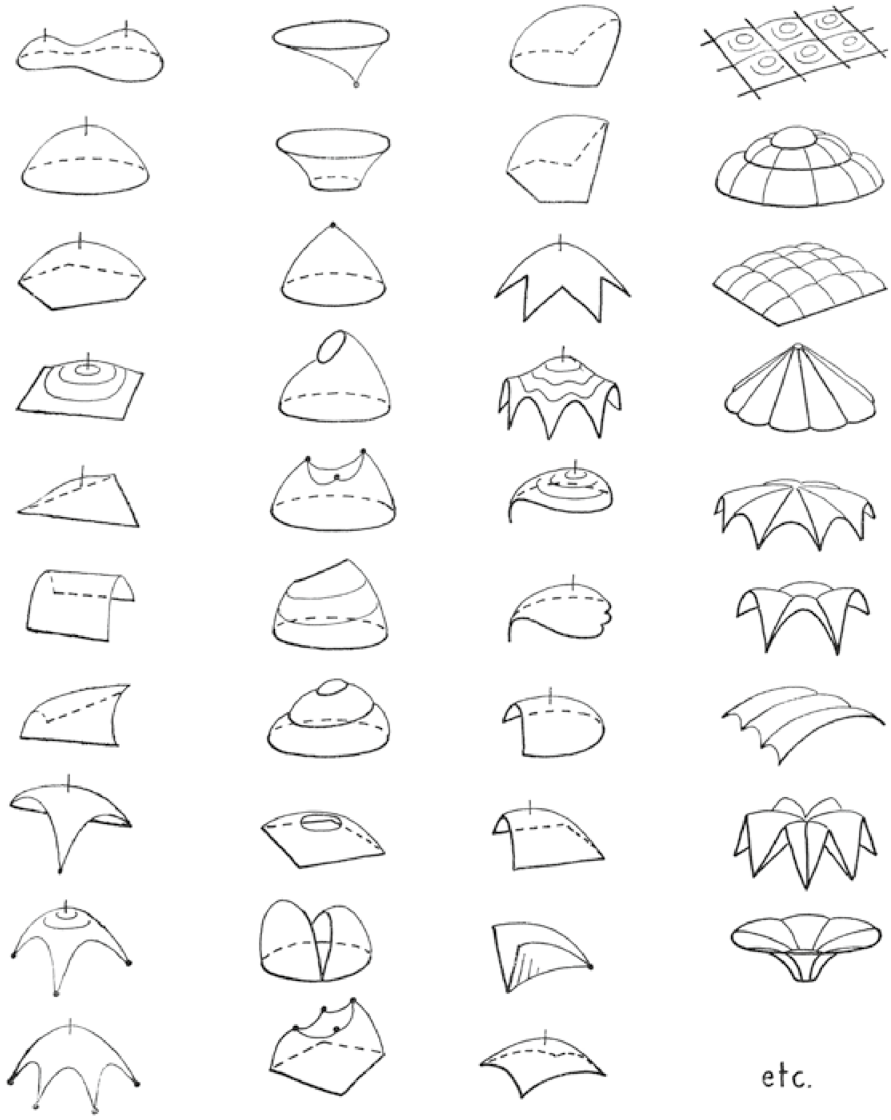
BUILDING AT ANY 'COST'

Complex architectural geometry typically comes at the expense of structural elegance and construction efficiency. Shell structures can address the former with varying degrees of success, but they all too quickly become unconvincing if they do not also address the latter; that is, if they cannot be constructed in an efficient or generally appropriate manner that considers the important role of local, cultural, and (socio-) economic factors. Shells typically require full and rigid formworks. Furthermore, the materials used to build formwork shuttering are often used only once, as they are customised for a specific, doubly curved geometry. For example, Fabian Scheurer of designtoproduction has wistfully described the formwork for the construction of SANAA's Rolex Learning Center at the Ecole Polytechnique Fédérale de Lausanne (EPFL) in Switzerland (2009) as his first large-scale timber structure, though it only stood for a few months.[1]

Structures such as Scheurer's for the EPFL study centre are therefore frequently not competitive in a profit-driven market, particularly where labour is expensive. Although some freeform concrete shells have been realised in recent years, these contemporary examples are usually signature buildings, where budget, materials or other constraints are not necessarily a central concern. Though these structures serve their place, a wider variety of applications in more diverse contexts is possible.

DISCOVERING OPPORTUNITIES

Advances in computer graphics, and especially the rapidly expanding possibilities enabled by computer modelling and generation techniques have resulted in an explosion of formal explorations in architectural design. New and complex shapes can be generated regardless of their structural stability or feasibility. The structural solutions required to build these new shapes often use an 'awkward accumulation of materials' rather than 'resistance through form' as Eladio Dieste termed it.[2] This leads to an approach to building that is intellectually – and often also architecturally – unsatisfactory. For example, a lack



Heinz Isler, 'New Shapes for Shells', 1959

left: At the First Congress of the International Association for Shell Structures (IASS) in Madrid in 1959, Isler presented his paper 'New Shapes for Shells', which included an illustration of 39 playful sketched shapes for shells, with 'etc.' suggesting infinite variations.

of structural thinking during the design process leads to constructions such as Frank Gehry's Walt Disney Concert Hall in Los Angeles (2003), where the structural engineers come in later to bring the architect's imaginative sketches into three dimensions. Such a unidirectional process results in heavy structures, wasted materials and inelegant details.

Arguably, architecture has failed if it is merely a freeform skin with a substructure, like the flat building fronts propped up from behind on the set of a Western, where it is only an image lacking materiality. Concrete shell structures, if properly designed and constructed in a process involving both architects and engineers, are able to cover large spaces at minimal material cost through efficient compressive and/or tensile membrane stresses, becoming fully three-dimensional functional forms rather than just screens. Shell shapes now go beyond the optimised ideal shapes and typologies developed by engineers and mathematicians in the heydays of shells in the 1950s and 1960s. They are fluid in their potential, which is made possible by new design approaches and tools. However, history can teach us much more. Structural concepts from the past can become driving forces in contemporary design; for example, traditional rib patterns can drive an aesthetic. More importantly, new efficiencies in fabrication and construction inspired by forgotten or lost knowledge can bring the entire methodology full circle. Parametricism needs real structural and engineering innovations to differentiate itself from purely image-driven architecture and to realise the full potential of complex curved geometry.

Tracing the vagaries of the use or disuse of shell structures is not simply a matter of following changes in stylistic taste or fashion. Learning from the past helps us to build in the present with logic and restraint. Digital and technological innovations and advances now allow us to achieve complex and spectacular geometries almost regardless of material or financial cost. However, the planet's decreasing resources, and widening awareness and public opinion regarding the use of materials or size of carbon footprints demand that architects

Block Research Group (BRG) with Escobedo Construction, Prototype of cable-net and fabric-formed thin shell, Buda, Texas, 2015

This thin-shell prototype was formed using a lightweight, prestressed cable-net and fabric formwork using mainly standard shoring and scaffolding elements.

engage with these issues. Complexity for the sake of complexity, especially if accompanied by a disregard for material flows or financial resources, is not intrinsically interesting or stimulating. We need to be asking the question: can we do the same – or more – with less?

REIMAGINING THE TRADITIONAL

Parametricism favours complex geometry and curved surface structures and therefore demands a continued push towards increased research and innovation in shell structures. Additionally, it justifies the value of shells that can be more efficiently constructed through (pre-)fabrication or other methods to avoid material waste or to better integrate building technologies. In several ongoing projects, the Block Research Group (BRG) at ETH Zurich is developing novel design approaches for shells as well as exploring new construction methods and logics to create these expressive, resource-efficient structural forms. The work shows that structural engineering can go beyond making a given geometry produce true innovation, and that designing with constraints need not constrain progress.

Heinz Isler may have been teasing in 1959 when, in his illustration of 39 playful sketched shapes for shells, he simply included the abbreviation 'etc.' in the final space, leaving the door open for infinite variations,[3] but we now have the tools to realise his vision. Morphing from one shape to the next, we have a wide vocabulary of fully flexible possibilities at our disposal. Nevertheless, the appropriate use of materials or other, more locally distinct limitations must remain central to the design and construction of shells.

For the Fábrica de Cultura, an arts school in Barranquilla, Colombia, by Urban-Think Tank with the BRG and the Chair of Architecture and Building Systems, ETH Zurich (planned to enter the construction phase in 2016), the BRG designed a tile-vaulted shell for the auditorium within a number of strict specifications. The compression-only shell needed to span a space of 20 by 40 metres (65 x 130 feet) and be optimised for construction using local labour and materials. As well as being expressive, it also needed to meet the high room-acoustical standards necessary for a performance space – all within light budget limits. The project took full advantage of the 'thrust network

analysis' approach, which is a three-dimensional extenstion of graphic statics.[4] Thanks to the explicit control of the relation between the form and forces of the shell through geometrically connected diagrams, these multiple criteria could be satisfied simultaneously during the design process. The geometrically dependent form and force diagrams functioned as parametric models, constrained to generate exclusively compression-only solutions.

Tile vaults are unreinforced masonry structures made of bricks and fast-setting mortar. The technique allows for the construction of complex shell structures without the need for formwork, making them inherently more economic and less wasteful in terms of materials and labour. The tile vault of the auditorium in Barranquilla will be a self-supporting permanent formwork for the concrete shell, picking up dead load and reducing costs – of the formwork itself, but also of the foundations that would otherwise be needed to support it. This has the additional benefit that while the concrete cures for the required 28 days, construction and finishing will continue beneath the shell, further optimising building processes, time and costs. Reinterpreting traditional construction techniques within a set of locally defined constraints thus reveals that new, economically and materially optimised shell structures are feasible in a surprising context.

By foregoing the need for disposable formworks which are destroyed once construction is complete, and instead making the formwork a permanent and expressive part of the structure, the tile vault reduces waste from construction. Similarly, approaches that externalise supports or require minimal or no foundations represent efficient use of materials. Lightweight, flexible formwork systems can also reduce the amount of material needed, especially for the falsework. Shuttering can be replaced by fabric, and falsework such as scaffolding can be replaced by cables or rods supported by an external frame at its boundaries. The formwork system offers a degree of control over the shape so that it can be easily optimised for improved structural behaviour and other criteria. Expensive, unique or customised parts are reduced to the minimum.

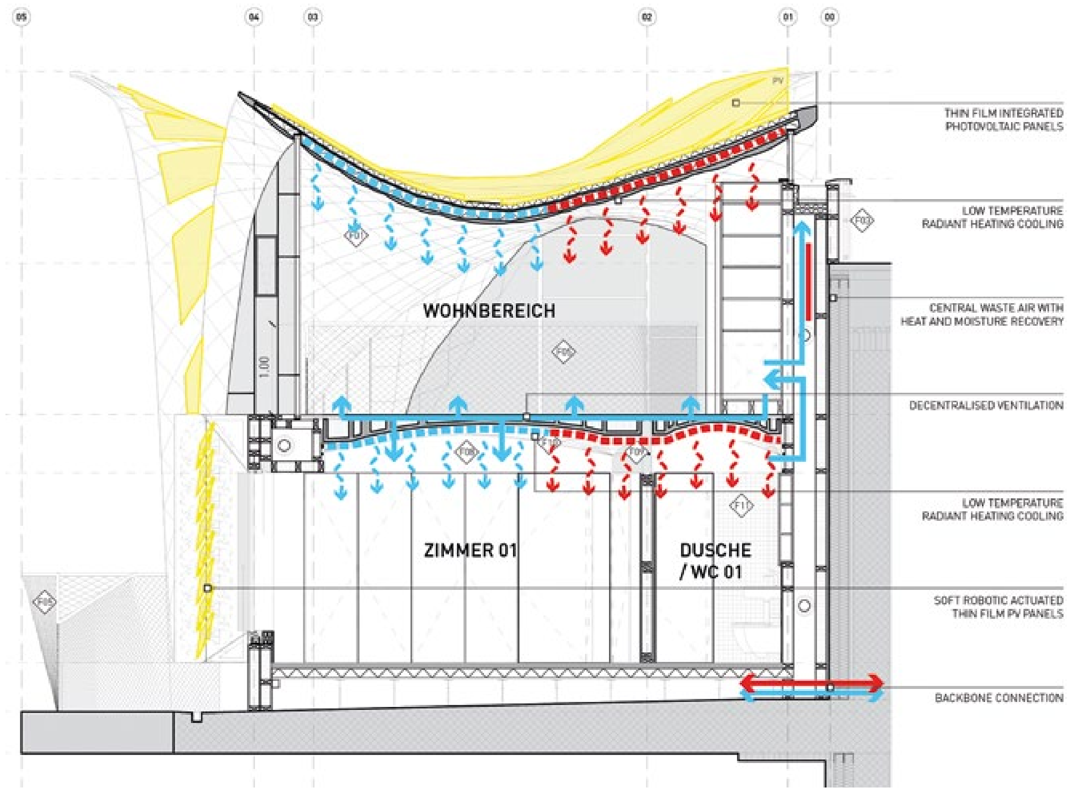
Block Research Group (BRG) and the Chair of Architecture and Building Systems (ETH Zurich) with supermanoeuvre and Zwarts & Jansma Architects, NEST-HiLo research and innovation unit, Dübendorf, Switzerland, due for completion in 2016

The HiLo unit on the NEST building on the Empa-Eawag campus, planned as a 16-by-9-metre (52-by-30-foot) duplex penthouse apartment for visiting faculty, features several innovations in lightweight construction such as a thin sandwich shell using a flexible tensioned formwork and a rib-stiffened funicular vault as the floor.

SUPERCHARGING SHELLS

Another area of potential for reduction is of course energy use. The NEST-HiLo research and innovation unit in Dübendorf, Switzerland, seeks to address many challenges related to the use of shell structures, including most prominently the issue of energy consumption and production, as well as the drastic reduction of required materials. Designed by the BRG and Chair of Architecture and Building Systems (ETH Zurich) with supermanoeuvre and Zwarts & Jansma Architects, the project (due to be completed in 2016) is more than just a shell with the singular function of simply spanning or covering, and is instead at once a structure, facade, insulation, a heating and cooling system, and a generator of energy.

The roof system is designed as a lightweight, doubly curved, thin sandwich shell structure, its shape structurally optimised to push the limits of what is



top: The HiLo shell functions as a radiator using a hydronic, low-temperature heating and cooling system and has high-efficiency thin-film photovoltaic cells applied on top. A structural sandwich shell with polyurethane foam insulation as its core solves the potential thermal bridge along the line of the glass facade, resulting in a continuous lower surface of architectural concrete.

possible in concrete. Its thinness and large surface area function like a radiator for heat transfer into the space within using a hydronic, low-temperature heating and cooling system. Polyurethane foam insulation will be used to achieve a low thermal transmittance at a small thickness. On top, optimally distributed, high-efficiency thin-film photovoltaic cells will be used for solar energy generation. To minimise thermal bridging, the connection between the glass facade and the shell demands the sandwich design, increasing the structural depth and reducing sensitivity to external loads and imperfections.

The floor design of the HiLo unit represents the most dramatic material savings within the NEST project. Its structure consists of a thin funicular vault made of concrete, stiffened by a system of fins on its extrados, and supported by the unit's primary frame structure at its four corners. These corners are connected by tension ties to absorb the horizontal thrusts of the funicular shell. This solution is inspired by built examples in tile vaulting in which thin vaults are stiffened by diaphragms, also called spandrel walls. The structural system is designed in cast concrete to achieve a thickness of only 2 centimetres (0.8 inches) for both vault and fins. Introducing funicular vaulting results in an extremely lightweight floor system with savings of more than 70 per cent in terms of both material and weight compared to prestressed, hollow-core slabs which are already considered to be optimal.

above: The structural system of the HiLo floor is a thin funicular vault made of unreinforced concrete, stiffened by a system of fins on its extrados and supported at its four corners by the primary structural frame. Connected by tension ties to absorb the horizontal thrusts of the funicular shell, the solution results in a thickness of only 2 centimetres (0.8 inches) for both vault and fins.

HiLo demonstrates the use of diaphragm-stiffened shells to extend the expressive language of the project while simultaneously following a logic that produces quantifiable savings. This unification is visible even in the pattern of the ribs on the floor vault, which was inspired by the ribbed masonry vaults of the past.

Designing shell structures is not only a matter of efficiency, but also of appropriateness – of materials, space, form, energy, cost and so on. Complex, intricate designs such as spiral shell staircases in which the landings smoothly transition to become the shells of roofs or floors are not far away. Such dreams are not merely fanciful diversions; they could become practical and efficient structures combining the complex curved geometries of Parametricism's methodology with the logic offered by advances in shell construction, an opportunity to be more than just a skin.[5] ⌂

Notes

1. Email communication with the author, 11 August 2015.
2. Eladio Dieste, 1997, as quoted in Remo Pedreschi, *Eladio Dieste: The Engineer's Contribution to Contemporary Architecture*, Thomas Telford Publishing (London), 2000, p 21.
3. Heinz Isler, 'New Shapes for Shells', International Colloquium on Construction Processes of Shell Structures, *IASS Bulletin*, 8, paper 3C, 1959, unpaginated.
4. Philippe Block, 'Thrust Network Analysis: Exploring Three-Dimensional Equilibrium', PhD dissertation, Massachusetts Institute of Technology Department of Architecture, 2009.
5. Thanks to Dr Noelle Paulson for her help with this chapter.